TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 64, Issue Special II, February, 2021

FINITE ELEMENT ANALYSIS OF THE EFFECTS OF THE VARUS ANGLE AND ANTERO-POSTERIOR TIBIAL INCLINATION ON THE STRESSES OF THE PROSTHETIC HUMAN KNEE

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Abstract: *In this study, six virtual models of the prosthetic human knee joint are developed and analyzed with the finite element method (FEA). The study is based on the virtual model of the human knee joint, as well as that of an existing knee prosthesis, often used in total knee arthroplasty, virtual models developed and presented in other previous works. Based on FEA, the effects of varus angle and antero-posterior tibial inclination (a-p.t.i) on the stresses developed in the components of the knee prosthesis are studied. Using AnsysWorkbench software, von Mises stress maps and maximum stress values are obtained for the six prosthetic knee assemblies and for each of the three components of the prosthesis: polyethylene insert, tibial component and femoral component. For each case of prosthesis-knee assembly (corresponding to a varus angle of 176^o, 182^o and 188^o, two variants were considered: an a-p.t.i of 0^0 and 5^0 respectively. The results show that as the varus angle increases, the von Mises stresses increase in all prosthesis components, and for an a-p.t.i of 5^o, the von Mises stresses decrease in all three components of knee prosthesis. The results, confirmed by clinical observations, suggest that the a-p.t.i of 5 ^{0} is favorable.*

Key words: *virtual knee prosthesis, prosthetic knee, FEA, von Mises stress, antero-posterior tibial inclination, varus angle*

1. INTRODUCTION

For the human body, the femur and tibia bones represent the pillars of support in daily activities, while the knee joint represents one of the most complex human joints, if we consider the large number of component elements, their varied structure, the different mechanical characteristics corresponding to each type of material.

The method of virtual modeling and the method of analysis with finite elements (FEA) used in the case of human bones and joints are increasingly used recently in research in orthopedics, traumatology, biomedical engineering, published in numerous papers [1-34]. By using these methods, it is possible to analyze the geometry of the contact, to study the effects of the material characteristics or type of implant on the biomechanical behavior of human bones or joints, to find maps of displacements and stresses in healthy and diseased bones and joints. FEA studies have been developed for normal and fractured bones [1-7] or provided with implants [8-18], for normal, osteoarthritic or prosthetic joints of lower limb, as well as of upper limb [21-23]. FEA allows researchers to test virtual human bones, joints, orthopedic implants or bone-implants assemblies and joints-implants assemblies to perform optimization and biomechanical behavior studies [6, 8, 14-20, 25, 35]. At the same time, FEA is often used to investigate the kinematic and dynamic behavior of the human musculoskeletal system [2-5, 9, 21-23] but also of bioinspired robotic structures, often used in rehabilitation or minimally invasive surgery [13, 26, 36-42].

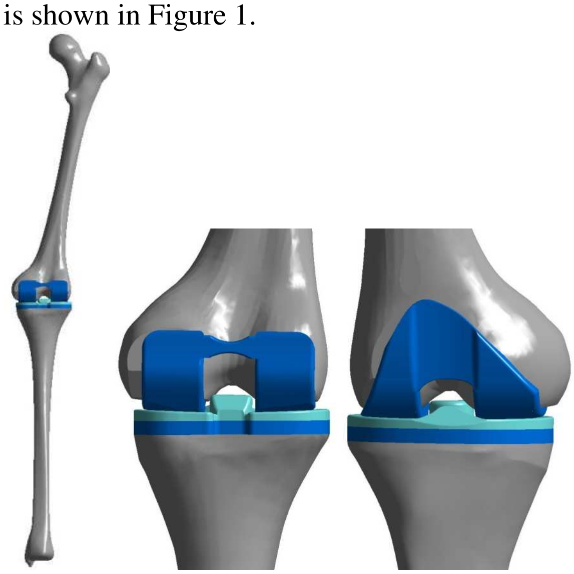
Virtual modeling and simulations of the healthy and osteoarthritic knee and FEA analyses of its biomechanical behavior, of tibiofemoral contact area, as well as the study of displacements and stresses occurred in the human knee joint under various loads were addressed in several articles [9-20]. For the prosthetic knee, FEA is often used to evaluate and make a comparison between the proposed design of a custom prosthetic component with a classic model, in order to optimize it, to assess the tibiofemoral contact stress [16-28, 35-38].

An important advantage of FEA consists into the flexibility of modeling operation with accurate control of loading conditions, of movement limitations and of structural changes. Failure of the total knee prosthesis is most often attributed to wear and tear of components that usually begin with the tibial component. The influence of antero-posterior tibial inclination (a-p.t.i) on total knee replacement surgery has been studied as a factor of major importance for prosthetic knee biomechanics and postoperative outcome [17, 30-35]. But its optimal value for the recovery of the knee joint function remains controversial. Bots cartilages, femoral and tibial, and their biomechanical behavior were virtually analyzed in healthy and osteoarthritic knee joint in [19].

The aim of this research is to examine the influences of the a-p.t.i on the values and distribution of stresses in the total knee prosthetic components by using FEA and numerical simulations on the virtual spatial models. This study will compare the values of the contact stresses and the behavior of the three prosthetic components for 6 different virtual models: three cases of varus inclination, each of them with 2 different sub-cases: antero-posterior tibial inclination angle equal to 0^{o} and 5^{o} respectively.

2. VIRTUAL MODELS OF THE KNEE JOINT-PROSTHESIS ASSEMBLY

The virtual model of the human knee joint was obtained with the help of advanced commands available in the software Ansys Workbench 15.07 [43], it being presented in detail in [10, 13]. Starting from 400 Computer Tomography cross sections made at a distance of 1.5 mm in the joint area and 2.5 mm for 15 cm away from the joint (top-down), the contour of the bones were created using SpaceClaim application, a preprocessor module of the AnsysWorkbench package. Contour lines were converted into 3D lines and then were exported to the advanced FEA DesignModeler preprocessor under the AnsysWorkbench application. Three-dimensional virtual solids of each knee component were created and, by using advanced modeling operations, the solids were obtained in the final form. In a similar way, starting with the geometry and dimensions of the Stryker prosthesis, one of the most commonly used prostheses by orthopedic surgeons for total knee replacement, virtual models of the three components of the knee prosthesis: femoral prosthesis (FP), tibial prosthesis (TP) and polyethylene insert (POLI) were obtained [29]. The virtual model of the prosthetic knee assembly, including the two bones: femur and tibia, and the three prosthetic components, for a biological varus inclination, is shown in Figure 1.



a) b)

Fig. 1. a) Virtual model of prosthetic knee a) entire assembly b) details (two views)

In the case of osteoarthritic process which implies the degradation of both knee cartilages: femoral and tibial, the angle formed by the tibia axis and the femur axis differs from the biological normal value of 176^{o}, depending of the process evolution and of the osteoarthritis gravity. For our study, a total number of six virtual spatial models of the prosthetic knee joint assembly corresponding to three different cases of varus inclination and, for each of them, two variants of a-p.t.i have been developed. The first case corresponds to 176°; the others two cases corresponds to real cases of varus inclinations in the osteoarthritic knee, 182° and 188°, being obtained by increasing this angle by 6° and 12°, respectively. The virtual models corresponding to the three different varus angles with 0° antero-posterior tibial inclination are presented in figure 2.

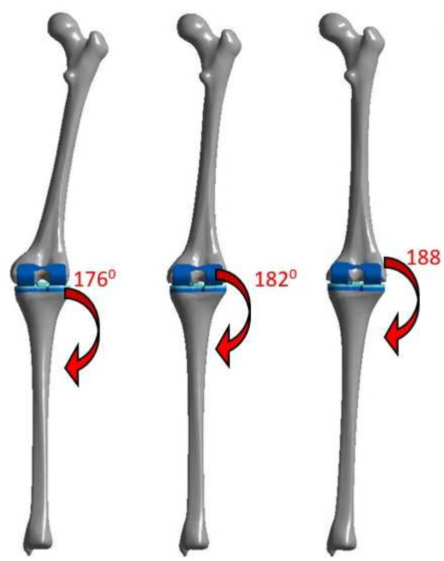


Fig. 2. Three cases of virtual model of prosthetic knee, with *varus* inclination equal to 176°, 182° and 188 °.

The optimal value of a-p.t.i performed by orthopedic surgeons during the resection of the tibial head in total knee arthroplasty is a very important factor for knee recovery and for preventing complications. Clinical observations highlight that in the case of a value of 5 ° a-p.t.i, it is simpler for orthopedic surgeons to mount the components of the knee prosthesis during total knee arthroplasty, while the range of f-e movement of the knee increases postoperatively.

In our study, the a-p.t.i equal to 0° and 5° respectively, were chosen for FEA due to the fact that the specialized companies, which provide knee prostheses, offers in both cases complete sets of surgical instruments for the surgical operation of total knee replacement. In order to achieve the virtual models with 5° antero-posterior tibial inclination, the head of tibia bone is cut under this angle, by comparing with classical inclination that are horizontal, equivalent with 0° antero-posterior tibial inclination. Following the cutting of the tibia bone in the anteroposterior direction, the T.P., the femur and F.P. were repositioned to establish new and correct contact areas (figure 3).

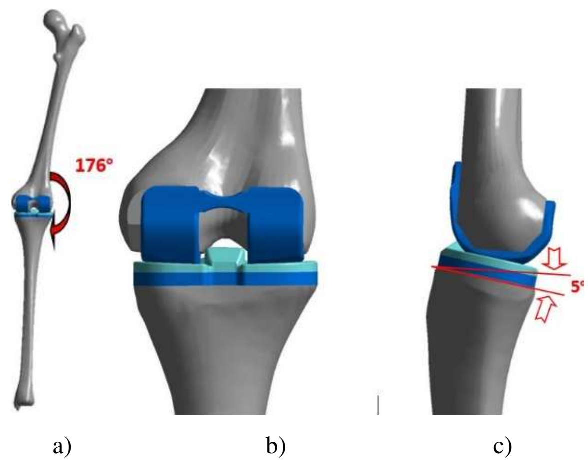
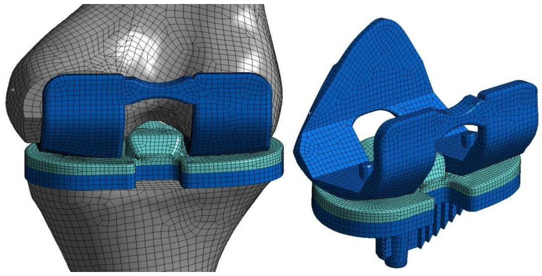


Fig. 3. Prosthetic human knee joint at 176° with anteroposterior inclination of 5°: a) prosthetic knee assembly; b) – Frontal view -detail; c) – Side view-detail

3. NUMERICAL SIMULATIONS AND FEA OF THE PROSTHETIC HUMAN KNEE

Using the AnsysWorkbench software, numerical simulations and FEM analyses were performed for the six cases of prosthetic knee with a-p.t.i of 0° and 5°, respectively. All components of the prosthetic knee joint assembly have been transferred in a XYZ system. For an optimized solution of the discretization and FEA process, the correct defining of the contact areas for avoiding the penetrations and the gaps between the components, and the different settings necessary for the FEA are required.

In order to obtain the mesh network and for better and more correct results, the finished solid elements: Solid186 hexahedral and Solid 187 tetrahedral, with medium nodes, with a size of 1.5 mm, were chosen for the areas of major importance for our study (figure 4). For the other areas characterised by a simplier geometry (as in the case of the dyaphisis of the femur or tibia) for discretisation process the elements with length of 2.5 mm were used, the passing from a size to the other being possible through the options "Smoothing" and "Transition".



a) b)

Fig. 4. a) Local view of the mesh network of prosthetic knee; b) –Isometric view.

The mesh network of the prosthetic knee with varus angle equal to 176^{o} (Table 1) is composed of 351324 nodes and 107128 elements, while for the other 5 cases the networks are similar, but with different number of nodes and elements.

Table 1

Nodes and elements for the virtual model corresponding to 176^{o} varus and 0^{o} a-p.t.i

Component	Nodes	Elements
Femur	144024	46321
Tibia	85185	26050
Femoral component	36180	10605
Tibia component	30479	8295
Polyethylene component	55456	15857
Total	**351324**	**107128**

Table 2 and table 3 show the mesh networks of the six discretized models of the knee-prosthesis assemblies.

Table 2

Nodes and elements used for analysis in the three cases with 0^{o} a-p.t.i

Anteroposterior tibial inclination 0^{0}	No. of Nodes	No. of Elements
176^{0}	351324	107128
182^{0}	347939	106853
188^{0}	338678	103666

Table 3

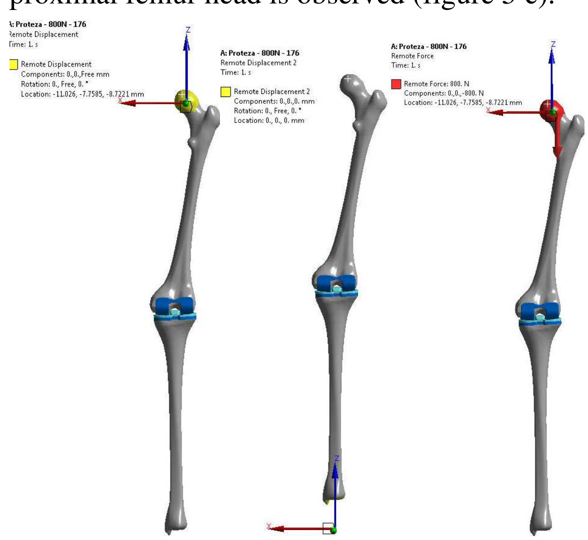
Nodes and elements used for analysis in the three cases with 5^{o} a-p.t.i

Anteroposterior tibial inclination 5^{0}	No. of Nodes	No. of Elements
176^{0}	377005	114266
182^{0}	369576	114126
188^{0}	373968	113265

For the contacts developed between the components considered for FEA analysis, the contacts named “Bonded” and “No-Separation” were used. In addition, the algorithm of “Augmented Lagrange" type is used, being recommended and efficient for contact models with large deformations, because of its flexibility features and of additional control allowed in order to reduce penetrations automatically. The detection method named "On Gauss Points", which implies a better understanding of the contact areas was supplementary used. This type of contact maintains the contact area in a "Stiking" closed contact.

The boundary and control conditions for analysis are as follows:

- virtual run time for analysis was set to 1 second;
- the solver was set as iterative by the level 2 PCG (“Preconditioned Conjugate Gradient”) method;
- using "Remote Displacement" option, the displacements were imposed and constrained for the movements considered in this analysis are: translation of the femur against the tibia (Z-axis), figure 5 a); rotation of the femur on the tibia head (Y-axis); rotation of the tibia around the ankle (Y-axis), figure 5b).
- a uniformly distributed "RemoteForce" on vertical directions (Z-direction) and equal to 800N is introduced on the coxofemoral joint; in red, the outline of the external surfaces of the proximal femur head is observed (figure 5 c).



a) b) c)

Fig. 5. a) Location for coxofemoral rotation and translation; b) Location of ankle rotation; c) Application area (red color) of the uniform distributed force.

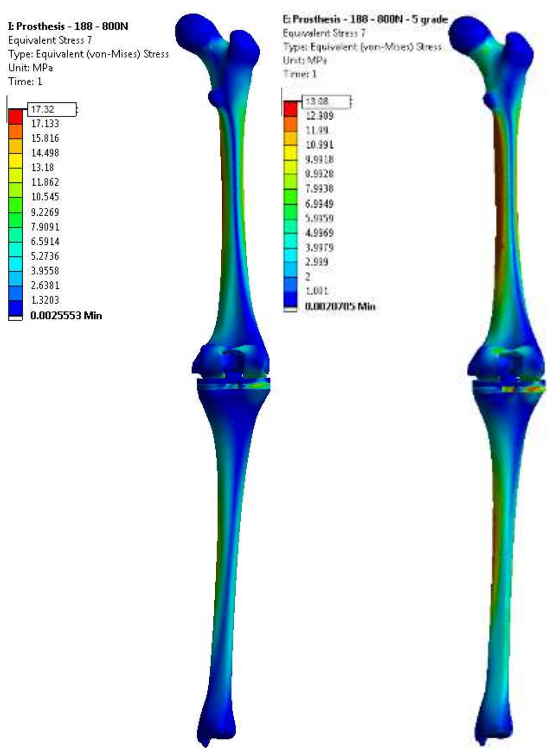
Based on previously published data [20], the characteristics of materials are assigned to each assembly' component as shown in table 4.

Table 4

Characteristics of materials [20]

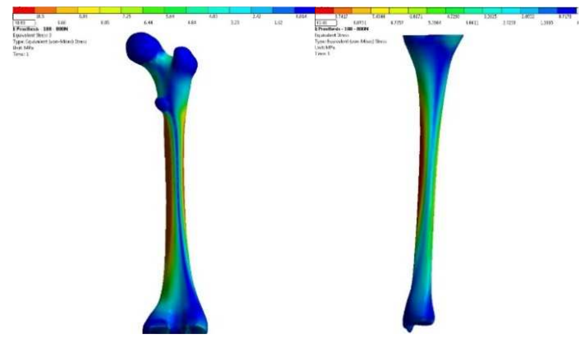
Geometry	Young's Modulus [MPa]	Poisson's Ratio
Femur	17,600	0.3
Tibia	12,500	0.3
F.P.	210,000	0.3
T.P.	210,000	0.475
POLI	1,100	0.42

Six finite element analyses were run. For each of them the maximum values and the distribution maps of von Mises stresses were obtained. Von Mises stress maps obtained for the entire assembly of prosthetic knee joint with varus angle of 188° for both cases of tibial inclination are shown in figure 6, while in figure 7 the stress maps are shown for femur and tibia bones.



a) b)

Fig. 6. Von Mises stress maps obtained for the prosthetic knee assembly with varus angle of 188° for: a) 0° a-p.t.i; b) 5° a-p.t.i



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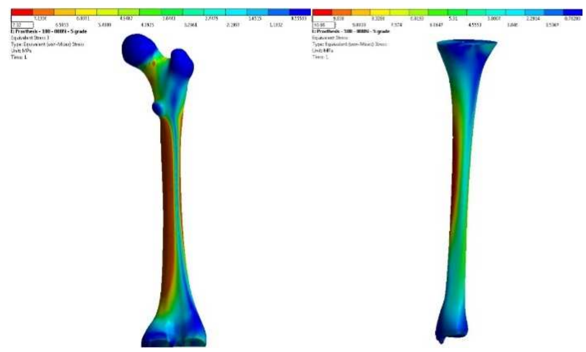
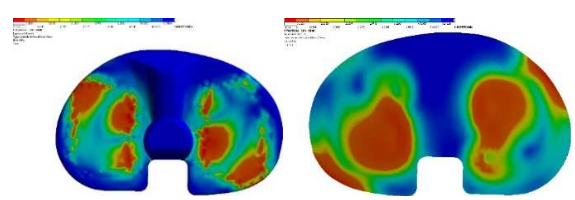


b)

Fig. 7. Von Mises stress distribution in femur and tibia respectively, for a varus angle of 188° for:
a) 0° a-p.t.i; b) 5° a-p.t.i

For our study, the stresses developed in the prosthesis components present a big interest. The maximum equivalent stresses (von Mises) developed in POLI, F.P. and T.P. for a loading force of 800N, applied on vertical direction on the femoral head, corresponding to the prosthetic knee with varus angle of 188°, both cases of tibial inclination, are shown in figure 8 and figure 9. In the same manner, the maps and the maximum values of von Mises stresses of the other four cases have been obtained.



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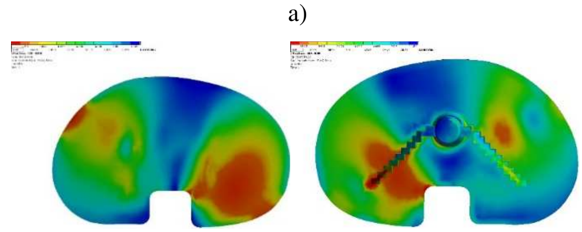

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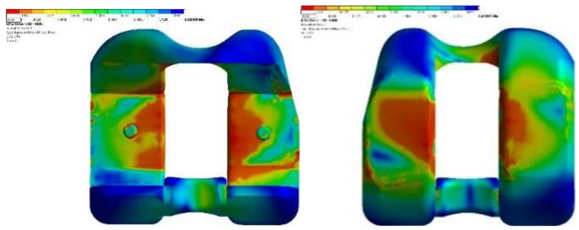
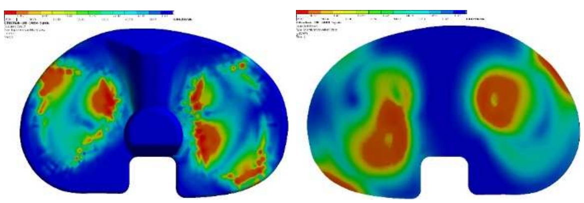


c)

Fig 8. Von Mises stress (Top view–left; Bottom view–right) in: a) POLI; b) T.P; c) F.P. for prosthetic knee with a varus angle of 188° - 0° a-p.t.i



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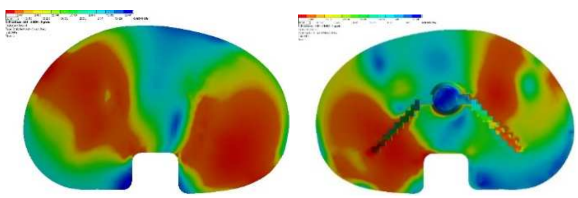

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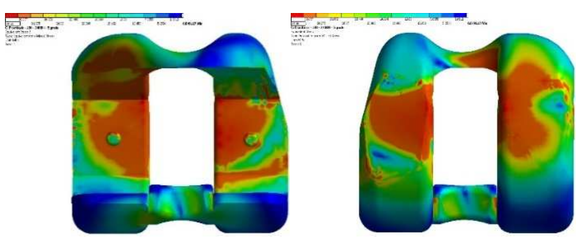

c)

Fig. 9. Von Mises stress (Top view–left; Bottom view–right) in a) POLI; b) T.P; c) F.P. for prosthetic knee with varus angle of 188° - 5° a-p.t.i.

Maximum values of von Mises stresses in tibia and femur bones, as well as in the three prosthetic components, for the 6 virtual models with 3 different angles of varus inclination and each of them with two different cases of a-p.t.i, for a loading force of 800N, are presented, in a synthesized form, in tables 5-6.

Table 5

Maximum von Mises stresses [MPa] obtained for varus models with 0° a-p.t.i and a load of 800N

Cases	POLI.	T.P.]	F.P.	Femur	Tibia
176⁰	18.14	16.82	17.28	10.45	14.08
182⁰	19.03	17.41	17.92	11.13	14.78
188⁰	19.97	18.39	18.58	11.79	15.37

Table 6

Maximum von Mises stresses [MPa] obtained for varus models with 5° a-p.t.i and a load of 800N

Cases	POLI.	T.P.	F.P.	Femur	Tibia
176⁰	14.08	12.85	13.25	6.01	10.15
182⁰	14.94	13.61	13.99	6.65	10.94
188⁰	15.91	14.82	14.85	7.13	11.62

The maximum values of von Mises stress on prosthetic knee components for both cases of an antero-posterior inclination of 0° and 5°, are shown in figure 10 and figure 11.

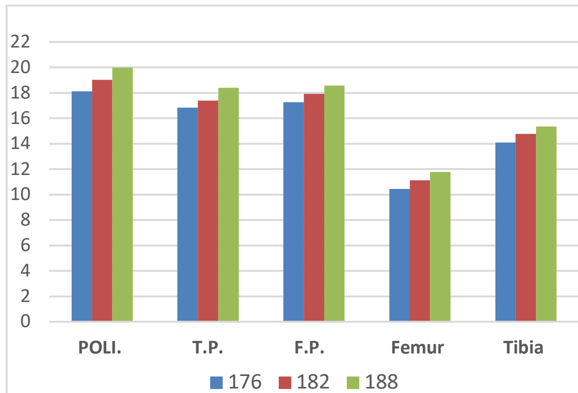

Fig. 10. Maximum von Mises stress on prosthetic knee (femur, tibia, POLI, T.P., F.P.) for 0° a-p.t.i

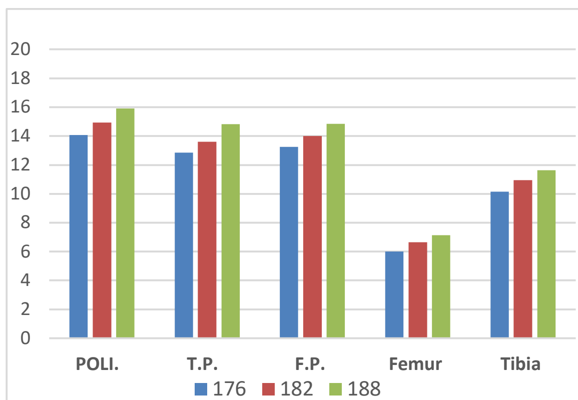

Fig. 11. Maximum von Mises stress [MPa] on prosthetic knee (femur, tibia, POLI, T.P., F.P.) for 5° a-p.t.i.

Studying the values in Tables 4-7, obtained as a result of numerical simulations and FEA, it can be seen that as the varus angle increases, the values of von Mises stresses increase for all three prosthesis components. For an a-p.t.i of 5°, the von Mises stresses decrease in all three components of the knee prosthesis, by comparing with the situation of 0° a-p.t.i. The results, confirmed by clinical observations, suggest that the a-p.t.i. of 5^0 is favorable**.** In all cases, the stresses values developed in all components of knee prosthesis present small differences, with higher values in POLI, and lower values in F.P. and T.P, respectively.

4. DISCUSSIONS

There are notable controversies in the choosing of the antero-posterior tibial inclination in total knee arthroplasty, considering the range between 0 and 10^o. Some surgeons use a higher tibial angle to obtain a higher knee flexion angle, but a large angle can easily lead to intra- and post-surgical complications. Small tibial inclination may cause an excessive cortical resection of the tibia, and, thus, causing the pitting of the prosthesis and, consequently, changes of tibial prosthesis inclination. High tibial inclination may cause increased posterior space affecting the posterior cruciate ligament, [35]. The normal antero-posterior tibial inclination was reported to be [6^o-9^o] [17].

The mean value of von Mises stresses distributed over the total contact area is situated in the range of [13-20] MPa. The values and the distribution of von Mises stress are similar to those obtained by Szivek in [18]. In [31], for orthostatic position (a 0-degree flexion angle), for a compressive force value equal to 3600 N, there resulted a von Mises stress value equal to 79.5 MPa, for 0° anteroposterior inclination, and 61 MPa for 6° anterior-posterior inclination. By comparing our results obtained for a loading force smaller 4 times (800N) (see tables 5 and 6) with those obtained by Shen, we can see that our values are about 4 times smaller and we can conclude that the differences are small and, consequently, the obtained values are validated

Taking into account that FEA analysis was run under similar conditions (homogeneous and isotropic materials, same type of prosthesis, same material and same contour conditions), the values obtained for von Mises stresses in this study are similar, with about 2-3% differences. For a compressive force of 800N, for a varus angle of 176° the maximum values obtained for von Mises stresses are similar to those obtained in [18].

5. CONCLUSIONS

In the present paper, the influences of the varus angle and a-p.t.i on the contact stresses in the components of the total knee prosthesis are studied. It is important to conclude that the maximum values of von Mises stresses are lower in the case of 5^o a-p.t.i than in the case of 0^o. Based on the FEA results obtained for the six cases studied, the conclusion suggesting that the tibial section should be made at a tibial inclination of 5 ° is validated by the clinical observations and overlaps with the results obtained in the study [18]. The results of the present study are clinically important, guiding the orthopedic surgeon to the optimum tibial cutting angle.

6. ACKNOWLEDGMENT

This research is supported by the funds of Project 546/2020, code PN-III-P2-2.1-PED-2019-3022, "Innovative modular robotic system for medical recovery of brachial monoparesis-NeuroAssist" funded by UEFISCDI.

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ANALIZA CU ELEMENTE FINITE A EFECTELOR UNGIULULUI DE VARUS ȘI A INCLINARII TIBIALE ANTERO-POSTERIORE ASUPRA TENSIUNILOR DIN GENUNCHIUL UMAN PROTEZAT

Rezumat: În această lucrare, pornind de la modelul virtual al articulației genunchiului uman și al unei proteze de genunchi existente, adesea utilizată în artroplastia totală a genunchiului, sunt elaborate șase modele virtuale ale articulației genunchiului uman protezat. Pe baza metodei elementelor finite, sunt studiate efectele unghiului de inclinare in varus și ale înclinarii tibiale antero-posterioare asupra tensiunilor dezvoltate în componentele protezei genunchiului. Folosind software-ul AnsysWorkbench, hărțile de tensiuni și valorile tensiunilor maxime von Mises sunt obținute pentru ansamblurile protezei genunchiului și pentru fiecare dintre cele trei componente ale protezei: insertul din polietilenă, componenta tibiala și componenta femurala. Pentru fiecare caz de ansamblu proteză-genunchi (corespunzător unui unghi varus de 176^o, 182^o și 188^o), au fost luate în considerare două variante: o înclinație tibială antero-posterioară de 0^0 și respective, de 5^0. Rezultatele arată că, odata cu cresterea unghiului de varus, cresc si tensiunile von Mises în toate cele trei componente ale protezei de genunchi, in timp ce pentru o înclinație tibială antero-posterioară de 5^o, tensiunile von Mises scad în toate componentele protezei. Rezultatele, confirmate de observațiile clinice, sugerează că panta tibială antero-posterioară de 5^0 este favorabilă.

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